USAELRDL Technical Report 2314

RADAR REFLECTION FROM A PLANETARY SURFACE DESCRIBED BY A COMPOSITE CORRELATION FUNCTION

Fred B. Daniels

May 1963

UNITED STATES ARMY
ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, N.J.

U. S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, NEW JERSEY

May 1963

Technical Report 2314 has been prepared under the supervision of the Institute for Exploratory Research, and is published for the information and guidance of all concerned. Suggestions or criticisms relative to the form, contents, purpose, or use of this publication should be referred to the U. S. Army Electronics Research and Development Laboratory, Fort Monmouth, New Jersey, Attn: Director, Exploratory Research Division "S".

J. M. KIMBROUGH, JR.
Colonel, Signal Corps
Commanding

OFFICIAL:
HOWARD W. KILLAM
Major, SigC
Adjutant

DISTRIBUTION:
Special

RADAR REFLECTION FROM A PLANETARY SURFACE DESCRIBED BY A COMPOSITE CORRELATION FUNCTION

Fred B. Daniels

DA TASK 3A99-25-003-04

ABSTRACT

An earlier theoretical study of radar reflection from a rough planetary surface is extended to include the case where the surface correlation function consists of two or more components. When both large- and small-scale structures are simultaneously present, it is found that the latter may completely dominate the autocorrelation function of the echo and thus render the former undetectable by c-w methods. An additional finding is that the large-scale structure may be detectable in the angular power spectrum obtained from very short pulses as a separate "pip" at the origin. Experimental confirmation for the lunar case is described. The effective radar gain of the surface derived by the methods of physical optics is found to have a maximum value of unity which leads to a minimum value of 3 for the dielectric constant of the surface. The spectrum of the surface fluctuations inferred from the wavelength-dependence of the surface slope is found to have a gap for components having a scale of the order of a few meters. Radar studies of larger-scale roughness by means of wavelengths much longer than ten meters would probably be rendered impossible by the terrestrial ionosphere. The shorter wavelengths demonstrate the existence of roughness having a scale of a few centimeters or tens of centimeters.

U. S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY

FORT MONMOUTH, NEW JERSEY

CONTENTS

	Page No.
Abstract	i
INTRODUCTION	1
SYMBOLS	1
SOME EARLIER RESULTS	1
THE COMPOSITE SURFACE CORRELATION FUNCTION	2
EFFECT OF THE COMPOSITE FUNCTION ON THE SPATIAL CORRELATION FUNCTION OF THE WAVEFRONT	3
EFFECT OF THE COMPOSITE FUNCTION ON THE ANGULAR POWER SPECTRUM	4
COMPARISON WITH EXPERIMENTAL RESULTS	5
THE DIFFUSE COMPONENT	5
THE EFFECTIVE GAIN AND THE DIELECTRIC CONSTANT OF THE LUNAR SURFACE	7
DETERMINATION OF THE SURFACE CORRELATION FUNCTION FROM RADAR OBSERVATIONS	8
DISCUSSION	9
CONCLUSIONS	10
ACKNOWLEDGMENT	10
REFERENCES	11

FIGURE

1. Reflected power as a function of delay 13

RADAR REFLECTION FROM A PLANETARY SURFACE DESCRIBED BY A COMPOSITE CORRELATION FUNCTION

INTRODUCTION

In a series of earlier USAELRDL reports[1-4] a general theory of radar reflection from a rough planetary surface was developed and applied to the interpretation of lunar radio echoes. The most important parts of these reports have been published in the Journal of Geophysical Research[5-7] and, since this publication is generally available, needless repetition will be avoided by referring to it, when applicable.

The purpose of this report is to consider the application to the moon in the case where the surface contains several different types of structure which may be represented by different terms in the surface correlation function. One of these terms is found to lead to a peak in the angular power spectrum which was only recently detected experimentally. The method used to compute the dielectric constant of the surface will be discussed, and it is found that a rigorous determination of this quantity would be quite difficult, but that an approximate result can be obtained by the methods of physical optics.

SYMBOLS

The following table defines the symbols used in this report. Additional symbols will be defined as they occur in the text.

- ξ displacement measured horizontally along the mean planetary sphere
- τ time coordinate
- λ radar wavelength
- $\overline{h^2}$ mean square surface amplitude ($\approx 1.85 \times 10^6$ m^2 for the lunar surface)
- α $16\pi^2\overline{h^2}/\lambda^2$
- f_o $2v/\lambda$, the Doppler shift at the moon's limb that results from the libration velocity v
- R lunar radius
- r distance measured along the lunar surface from the subterrestrial point

SOME EARLIER RESULTS

If $\gamma(\tau)$ is the normalized autocorrelation function of the height-variations at the subterrestrial point that result from the lunar libration, the normalized autocorrelation function of the envelope of the radar echo will be[5]

$$P(\tau) = \exp\{-\alpha[1 - \gamma(\tau)]\} \; . \qquad (1)$$

Because of the relation $2\xi/\lambda = f_o\tau$, $\gamma(\tau)$ is the same function of $f_o\tau$ that $\rho(\xi)$, the normalized spatial correlation function of the surface, is of $2\xi/\lambda$, and the two functions may therefore be used interchangeably.

The angular power spectrum of the scattered radiation has been shown to be[5]

$$p(r/R) \propto \cos^2(r/R) \int_0^\infty \xi\, J_o(2kr\xi/R)\, \cos(k\xi^2/R)\, \rho_E(\xi) d\xi \qquad (2)$$

where $\rho_E(\xi) = \exp\left\{-\alpha\left[1 - \rho(\xi)\right]\right\}$. (3)

(In earlier publications by the author, the term before the integral sign was given as $\cos\theta$. More detailed consideration leads to the result that it should be $\cos^2\theta$.) At wavelengths used in lunar experiments, $\rho_E(\xi)$ is found to fall to very small values before the cosine term in the integrand has departed appreciably from unity. The latter may therefore be omitted and, placing $r/R = \theta$, we obtain

$$p(\theta) \propto \cos^2\theta \int_0^\infty \xi\, J_o(2k\xi\theta)\, \rho_E(\xi) d\xi \ . \qquad (4)$$

It should be emphasized that omission of the $\cos(k\xi^2/R)$ term will cause the so-called "residual smooth surface reflection" to be missing from the final result. Since some of the recently published theories[8,9,10] do not have this term in the integrand, the results obtained are incomplete in that they do not approach the Fresnel-zone oscillations of the smooth surface reflection as the amplitude of the surface irregularities becomes vanishingly small. It should also be emphasized that a number of approximations were made in deriving equations 1 to 4, among which are the assumptions that $\sin\theta = \theta$ and $\cos\theta = 1 - \theta^2/2$. In addition, the slope of the surface elements relative to the mean sphere was assumed to be small relative to unity.

THE COMPOSITE SURFACE CORRELATION FUNCTION

In recent theoretical studies, the lunar surface has been described by a single Gaussian or exponential correlation function,[8,10] or else by one such component and a second diffusely scattering component that was not expressed in terms of a correlation function.[9,11] Since telescopic studies of the moon show the existence of structures of two different magnitudes, namely, a) the mountains and maria, and b) the craters, it would be more realistic to adopt a composite surface correlation function having at least two components. If A' and A'' are the relative contributions of these two components to the normalized surface correlation function $\rho(\xi)$, we can write

$$\rho(\xi) = A'\ \rho'(\xi) + A''\ \rho''(\xi) \qquad (5)$$

where $A' + A'' = 1$. In order to do this, $\rho'(\xi)$ and $\rho''(\xi)$ must be assumed to be uncorrelated, since only in this case will the function $\rho(\xi)$ be equal to the sum of the component functions. The functions $\rho'(\xi)$ and $\rho''(\xi)$ may have any functional form but, in the following discussion, will be assumed to be Gaussian, because of the ease with which this form can be treated mathematically. If an exponential correlation function were assumed, the angular power spectrum $p(\theta)$ could be obtained only as a doubly infinite series which would converge very slowly unless the rms amplitude were much smaller than the radar wavelength. This obviously would not be true except, possibly, for the diffuse component.

EFFECT OF THE COMPOSITE FUNCTION ON THE SPATIAL CORRELATION FUNCTION OF THE WAVEFRONT

If $\rho'(\xi)$ and $\rho''(\xi)$ in equation (5) are assumed to have Gaussian form, the spatial correlation function $\rho_E(\xi)$ of the reflected wavefront becomes

$$\rho_E(\xi) = \exp\left\{-\alpha\left[1 - A' \exp(-\xi^2/L^2) - A'' \exp(-\xi^2/\ell^2)\right]\right\} \tag{6}$$

where L and ℓ are the structure sizes of the two components, and L is assumed to be much larger than ℓ. The additional assumption is made that $A' \gg A''$.

An autocorrelation function has already been computed from Hayn's map of the limb regions of the moon[5] and, since the ordinates were taken at points separated by one degree ($\approx$ 30 km) along the periphery, it may be assumed that this correlation function is mainly representative of the major structures (the mountains and maria) and is not greatly affected by the craters. If a Gaussian is fitted to this correlation function, we find that $L = 10^5$ m. Furthermore, the value of $\overline{h^2}$ is found to be 1.85×10^6 m^2, which leads to $\alpha = 6.3 \times 10^8$ at 68 cm wavelength, one used by Evans and Pettengill for much of their work.[12]

It can readily be seen that, as the variable ξ runs through a range of values from zero to one somewhat larger than ℓ, $\rho_E(\xi)$ will asymptotically approach $\exp -\alpha(1-A')$. If A' is not too close to unity, this asymptotic value will be quite small because of the large numerical value of α. This result shows that, when large and small structures are simultaneously present, the latter will completely dominate the function $\rho_E(\xi)$, since $\exp(-\xi^2/L^2)$ will remain near unity until $\rho_E(\xi)$ has become vanishingly small. The practical significance of this result is that no information can be obtained about the existence of the large-scale structure from observations of $P(f_o\tau)$, the autocorrelation function of the signal, since $P(f_o\tau)$ is the function $\rho_E(\xi)$ with

a change of variable.

EFFECT OF THE COMPOSITE FUNCTION ON THE ANGULAR POWER SPECTRUM

To examine the effect of the composite surface correlation function on the angular power spectrum $p(\theta)$, we shall introduce the expression for $\rho_E(\xi)$ given by equation (6) into equation (4) and use the second law of the mean for integrals to separate $p(\theta)$ into two functions, one of which represents the large-scale structure only. To carry out this procedure, $\rho_E(\xi)$ is first rearranged to read

$$\rho_E(\xi) = \exp\left\{-\alpha\left[1 - A' \exp\left(-\xi^2/L^2\right)\right]\right\} \cdot \exp\left[\alpha A' \exp\left(-\xi^2/\ell^2\right)\right]. \tag{7}$$

When the numerical values of L and α are substituted into this relation, it is found that $\rho_E(\xi)$ is not appreciably altered when $\exp(-\xi^2/L^2)$ is approximated by the first two terms of its series expansion and this simplification leads to

$$\rho_E(\xi) = \exp\left[-\alpha(1 - A')\right] \cdot \exp\left(-\alpha A'\xi^2/L^2\right) \cdot \exp\left[\alpha A' \exp\left(-\xi^2/\ell^2\right)\right]. \tag{8}$$

After substituting (8) into (4), we obtain

$$p(\theta) \propto \cos^2\theta \int_0^\infty \varphi(\xi)\, f(\xi,\theta)\, d\xi \tag{9}$$

where $\varphi(\xi) = \exp\left[\alpha A' \exp\left(-\xi^2/\ell^2\right)\right]$

and $f(\xi,\theta) = \exp\left(-\alpha A' \xi^2/L^2\right) \xi J_0(2k\xi\theta)$.

Since $\varphi(\xi)$ is a positive monotonically decreasing function of ξ, the second law of the mean for integrals is applicable and equation (9) can be expressed as

$$p(\theta) \propto \varphi(0) \cos^2\theta \int_0^x f(\xi,\theta)\, d\xi \tag{10}$$

where $0 \le x \le \infty$. The integral in (10) can be expressed formally as the difference between two integrals, one from 0 to ∞, and one from x to ∞ . The first of these can be evaluated in closed form and the second is a function of θ which cannot be evaluated because the value of x is unknown. The final result is found to be

$$p(\theta) \propto \left[\frac{L^2}{2\alpha A'} \exp\left(-\theta^2/\theta_0^2\right) + F(\theta)\right] \cos^2\theta \tag{11}$$

where $\theta_0^2 = 4 A' \overline{h^2}/L^2$ and $F(\theta)$ is an unknown function of θ. The first term on the right is approximately the angular power spectrum that would result from the large-scale structure alone (since $A' \approx 1$). We have therefore shown that it is possible to exhibit $p(\theta)$ as the sum of two functions, one of which represents the large-scale structure. Whether this procedure has any physical

significance, however, could only be determined by experiment.

COMPARISON WITH EXPERIMENTAL RESULTS

When numerical values are substituted into the first term of equation (11), it is immediately apparent that experimental confirmation of the existence of this component might not be possible with low resolution radars. Expressed in terms of delay, this term becomes, for small values of θ,

$$10 \log_{10} \exp\left(-\theta^2/\theta_0^2\right) = -1.2\,\tau \text{ (db)} \tag{12}$$

where τ is given in microseconds. Most experimental work to date has been done with range resolutions of 10 μsec or more and equation (12) shows that the angular power spectrum would drop off 12 db during a 10 μsec interval.

Some recent lunar results have been reported by Mehuron[13] that were carried out with equipment having a maximum resolution capability of 1.8 μsec. In the case of the reported experiment, however, the equipment was operated with a resolution of 3.1 μsec. Since the frequency of this radar is 425 Mc, the foregoing calculations (which were based on 440 Mc) are applicable. Figure 1 shows the observed angular power spectrum plotted as a function of delay, together with equation (12) (plotted relative to an arbitrary level). The agreement is seen to be quite good in view of the approximations made at various stages of the analysis.

A different interpretation of the experimental result was offered by Mehuron, who suggested that it might be a specular reflection from a flat area near the leading edge of the moon. However, on one of the occasions when this reflection was obtained, the subterrestrial point fell on the rim of the crater Pallas, in the midst of generally rugged terrain, and it does not appear probable that a flat surface large enough to reflect much energy (i.e., one as large as the first Fresnel zone) could have existed in this region.

With the addition of the new information provided by Mehuron's data, it now appears that the angular power spectrum of the lunar echo has three distinct components. One of these has now been shown to be attributable to the largest surface features, i.e., the mountains and the maria. In the light of this interpretation, we can be reasonably certain that the second component can be attributed to the lunar craters. The third component (the so-called "diffuse" component) must still be accounted for, and this will be discussed in the next section.

THE DIFFUSE COMPONENT

The diffuse component, which accounts for about 20% of the radar echo at 68-cm wavelength and 30% at 3.6 cm, has been attributed by Evans and Pettengill[12]

to scattering by surface irregularities of the order of magnitude of the radar wavelength. However, the theory upon which the present report is based is not rigorously applicable to scattering by objects whose horizontal and vertical scales are both of the order of the wavelength, since this would violate the original assumption that the average slope is small. The following discussion shows how the angular power spectrum derived by the methods of physical optics behaves as the horizontal scale of the irregularities decreases, and this is followed by a discussion of a modification which takes into account the increase in the slope which results as the horizontal scale approaches the vertical scale.

If only the small-scale component is assumed to be present and its correlation function is exp $(-\xi^2/\ell^2)$, substitution into (3) results in an expression for $\rho_E(\xi)$ that can be expanded into an infinite series. If this series is then substituted into (2) and a term-by-term integration is performed, the final result becomes

$$p(\theta) \propto e^{-\alpha} \cos^2\theta \left\{ (R\lambda/4\pi) \sin (2\pi\theta^2 R/\lambda) + \ell^2 \sum_{n=1}^{\infty} \frac{\alpha^n}{2n!n} \exp (-k^2\ell^2\theta^2/n)\right\} . \qquad (13)$$

The sine term represents the residual smooth surface reflection and gives the Fresnel-zone oscillations of this component. If $\overline{h^2} \ll \lambda^2$, α will be small and the series will converge so rapidly that the remainder of the solution can be approximated by the term for n = 1. For small values of $2\pi\ell/\lambda$, this term indicates that contributions are received over a wide range of values of θ, and this portion of the solution therefore represents the diffuse component.

As the quantity $2\pi\ell/\lambda$ approaches zero, however, a smoothing of the wavefront occurs, because the incident radiation cannot penetrate crevices which are small relative to $\lambda/2\pi$. Feinstein[14] has found that this smoothing can be allowed for by replacing the quantity α in (13) by

$$\alpha' = \frac{\alpha}{1 + \frac{4\alpha}{(k\ell)^2}} . \qquad (14)$$

That this correction is related to the increase in the slope as ℓ decreases can be seen by noting that, for a surface described by a gaussian correlation function, the mean square slope m^2 is $2\overline{h^2}/\ell^2$, and the denominator in (14) is therefore $8m^2$. This procedure is not completely rigorous, however, since Feinstein noted that cross-polarization effects may be expected whenever replacement of α by α' is necessary.

A treatment of "slightly rough" surfaces (i.e., those for which $\overline{h^2} \ll \lambda^2$) which includes polarization effects has been given by Peake,[15] who based his work on an earlier study by Rice.[16] Peake shows that the angular power spectrum is given by an integral similar to the one in equation (4), except that there are separate solutions for vertical and horizontal polarization, the integral being multiplied by a factor which depends upon the dielectric constant, the angle θ, and the polarization. The work by Peake, together with associated experimental work by Taylor,[17] demonstrates that the diffuse component of the lunar echo could be caused by surface roughness for which $\ell \ll \lambda$, since the results for various surfaces for which this condition holds closely resemble the diffuse component of lunar echoes. Even the polarization effects observed (a relative decrease in the horizontally polarized component with increasing obliquity) could account qualitatively for the decrease in percent polarization towards the limb observed in lunar studies.[12]

The work of Peake and Taylor leads to the conclusion that the diffuse component may occur even for the case of small slopes as a result of ℓ becoming smaller than the wavelength. However, the preceding discussion based on physical optics shows that it could also arise when both ℓ and $(\overline{h^2})^{1/2}$ are of the order of the wavelength. In fact, Rice[16] has shown from physical considerations that, for the case of vertical incidence, a surface roughness component equal to the radio wavelength can cause considerable scattering out of the main beam, and his argument can easily be extended to the case of oblique incidence.

THE EFFECTIVE GAIN AND THE DIELECTRIC CONSTANT OF THE LUNAR SURFACE

When either physical optics[5] or electromagnetic theory[11] is used to compute the total average power reflected from a rough sphere having surface irregularities that are larger than the wavelength, the result is found to be the same as that for a smooth sphere. In other words, the effective gain is unity. This result does not depend upon any assumption regarding the form of the surface correlation function and would, therefore, hold for a composite function such as that given by equation (5). The question arises, however, as to what happens when the structure size becomes as small as, or smaller than the wavelength, because it is such structure that is presumed to be responsible for the diffuse component of the echo. Feinstein[14] has computed the effective gain of a rough infinite plane for small values of ℓ/λ by computing the total reflected power from the angular power spectrum after it has been modified by replacing α by the α' given by (14). The result of this procedure

is that the gain is found to approach unity for $\ell \gg \lambda/2$ and also for $\ell \ll \lambda/2$. However, for $\ell \approx \lambda/2$, the gain decreases, attaining values of approximately 0.8 and 0.7 for $\overline{h^2}/\lambda^2 = 1/8\pi^2$ and $1/1.6\pi^2$, respectively. The corresponding results for a sphere could be obtained by suitably changing the parameters in Feinstein's equations. However, since the predominating factor is an inverse distance effect which would be negligible for the moon, the gain in this case would be close to unity over a wide range of values of $\overline{h^2}/\lambda^2$.

The gain computed by the foregoing method has been called the effective gain[12] rather than the reflectivity, since it would exist in the case of a perfectly reflecting material with a roughened surface. For a surface having a reflectivity ρ if perfectly smooth, the effective reflectivity would be the product of ρ and the effective gain g. Since the effective lunar reflectivity is 0.07 at 68-cm wavelength, we would have $g\rho = .07$ and an assumed value of 1.0 for g would give $\rho = .07$. Substituting this value of ρ into the usual formula relating conductivity and dielectric constant κ, leads to a value of $\kappa = 2.95$. The smallest possible value of κ based on the observed radar cross-section would therefore be about 3, even when the diffuse component is included.

Since the foregoing analysis is based upon physical optics, it is not completely rigorous. Cross-polarization and shadowing effects could modify the result.

DETERMINATION OF THE SURFACE CORRELATION FUNCTION FROM RADAR OBSERVATIONS

In an earlier publication,[4] the surface correlation function $\rho(\xi)$ was computed from the observed autocorrelation function $P(f_0\tau)$ by means of equation (1). The results were probably in error, because, as pointed out in a later paper,[7] $P(f_0\tau)$ contained a considerable amount of high-frequency energy from the diffuse component of the scattering, which should have been subtracted out. The calculation could, of course, now be repeated, using the corrected function $P(f_0\tau)$. This has not been done, however, because the result would probably be of little practical value. The function $\rho(\xi)$ is obtainable by this method only for a very limited range of the variable ξ and furthermore, the vertical scale of the correlation function is so greatly expanded that the small differences between the curves corresponding to different wavelengths may be meaningless. Information of much greater value regarding the surface roughness can be obtained by studying the effect of wavelength change on the surface gradient. Such studies indicate that the surface gradient remains constant

as the wavelength is reduced from 784 cm to 68 cm,[6,7] but then increases as the wavelength is decreased from 68 cm to 3.6 cm.[12] This behavior would appear to indicate that a gap exists in the spectrum of the surface fluctuations for components having a "wavelength" of the order of magnitude of a few meters.

DISCUSSION

With the addition of the new experimental data of Mehuron,[13] the angular power spectrum of lunar radio echoes is now known to consist of three distinct portions and the spectrum of the surface roughness would, therefore, also have three distinct regions. The physical features corresponding to these spectral regions are a) the mountains and maria, b) the craters, and c) small-scale roughness having a scale of the order of one meter or less.

The conclusion that the diffuse component arises from scattering by surface elements having a scale not larger than one meter is supported by the fact that the scattering properties deduced from both the autocorrelation function and the two-frequency cross-correlation measurements appear to be the same at 784 cm and 68 cm.[6,12] This would imply that any small-scale roughness present cannot have a scale appreciably greater than 68 cm. However, a further decrease in the wavelength from 68 cm to 3.6 cm does result in a change in the scattering properties,[12] which implies the existence of structure having a scale smaller than 68 cm. Although the work of Peake[15] and Taylor[17] indicates that the diffuse echo could be caused by structure of the order of millimeters, the increase in the measured slope as the wavelength is decreased from 68 cm to 3.6 cm[12] would seem to indicate that structure of the order of a few centimeters or tens of centimeters is present.

The lack of structure having a scale much larger than a meter is pertinent to recent discussions regarding the existence of roughness which might affect the mobility of lunar vehicles.[18-20] Unfortunately, radar determinations of surface slopes have not been made at wavelengths larger than 784 cm and probably could not be made because of complications that would be introduced by the terrestrial ionosphere. Consequently, there is still a large unexplored region of the roughness spectrum extending up to a structure size of the order of 300 meters, the diameter of the smallest craters that can be seen telescopically.

The minimum value of 3 for the dielectric constant implies a fairly substantial surface. If the moon is covered by "cobwebby fairy castles" as recent newspaper reports suggest, this fragile layer would have to be much less

than a meter in thickness, or else be so ethereal that it would not affect the measurement of the dielectric constant of the underlying layer.

CONCLUSIONS

Representation of the lunar surface by a composite surface correlation function leads to several results that are of value in the interpretation of radar experiments. One result is that when small-scale and large-scale structures are both present, the small-scale effects dominate the autocorrelation function of the signal envelope, and the existence of the large-scale irregularities cannot, therefore, be detected by c-w measurements.

A second result is that large-scale structures which have large vertical amplitudes may produce a detectable "pip" at the origin of the angular power spectrum. Examination of the results of recent experimental studies made with a high resolution radar confirms the existence of this pip, and comparison with theory demonstrates that it is derivable from the autocorrelation function of the large-scale features. This shows that, in the case of the moon, the two major types of surface formations are responsible for distinctly different portions of the quasi-specular part of the angular power spectrum.

It is concluded that the diffuse component observed at meter wavelengths probably results from structure of the order of a few centimeters or tens of centimeters.

The methods of physical optics lead to a minimum value of 3 for the dielectric constant of the lunar surface.

Studies of the wavelength-dependence of the average surface gradient indicate that a gap exists in the spectrum of lunar surface fluctuations for components having a "wavelength" of the order of a few meters. The region from about 10 meters upwards, however, is still unexplored by ground-based radar and will probably remain so.

ACKNOWLEDGMENT

I am greatly indebted to Mr. Mehuron for calling his experimental work to my attention and for permitting me to use his data before its publication.

REFERENCES

1. F. B. Daniels, "Radar Determination of the Surface Structure of the Moon," USASRDL TR 2110, 1 April 1960.

2. F. B. Daniels, "The Angular Power Spectrum of Lunar Radio Echoes," USASRDL TR 2129, 25 May 1960.

3. F. B. Daniels, "A Theory of Radar Reflection from the Moon," USASRDL TR 2163, November 1960.

4. F. B. Daniels, "Radar Determination of the Statistics of the Lunar Surface," USAELRDL TR 2304, August 1962.

5. F. B. Daniels, "A Theory of Radar Reflection from the Moon and Planets," J. Geophys. Research, 66, 1781 (1961).

6. F. B. Daniels, "Radar Determination of the Root Mean Square Slope of the Lunar Surface," J. Geophys. Research, 68, 449 (1963).

7. F. B. Daniels, "Radar Determination of Lunar Slopes: Correction for the Diffuse Component," J. Geophys. Research, 68, 1 May 1963 (to be published).

8. J. K. Hargreaves, "Radar Observations of the Lunar Surface," Proc. Phys. Soc., B73, 536 (1959).

9. T. Hagfors, "Some Properties of Radio Waves Reflected from the Moon and their Relation to the Lunar Surface," J. Geophys. Research, 66, 775 (1961).

10. V. A. Hughes, "Diffraction Theory Applied to Radio Wave Scattering from the Lunar Surface," Proc. Phys. Soc., 80, 1117 (1962).

11. D. F. Winter, "A Theory of Radar Reflections from a Rough Moon," J. Research NBS, 66D, 215 (1962).

12. J. V. Evans and G. H. Pettengill, "The Scattering Behavior of the Moon at Wavelengths of 3.6, 68, and 784 Centimeters," J. Geophys. Research, 68, 423 (1963).

13. W. O. Mehuron, "High Resolution Lunar Measurements," National Aerospace Conference, Dayton, Ohio, 20 May (1963).

14. J. Feinstein, "Some Stochastic Processes in Wave Propagation, Part I," Trans. IRE, AP2, 23 (1954).

15. W. H. Peake, "Theory of Radar Return from Terrain," IRE Convention Record, Part I, 27 (1959).

16. S. O. Rice, "Reflection of Electromagnetic Waves from Slightly Rough Surfaces," The Theory of Electromagnetic Waves. (Interscience Publishers, Inc., New York, 1951).

17. R. C. Taylor, "Terrain Return Measurements at X, K_u, and K_a Band," IRE Convention Record, Part I, 19 (1959).

18. C. D. Mc Gillen and B. P. Miller, "Lunar Surface Roughness from Crater Statistics," J. Geophys. Research, 67, 4787 (1962).

19. J. W. Salisbury, "Discussion of a Paper by C. D. Mc Gillen and B. P. Miller, 'Lunar Surface Roughness from Crater Statistics,'" J. Geophys. Research, 68, 2065 (1963).

20. C. D. Mc Gillen and B. P. Miller, "Reply," J. Geophys. Research, 68, 2066 (1963).

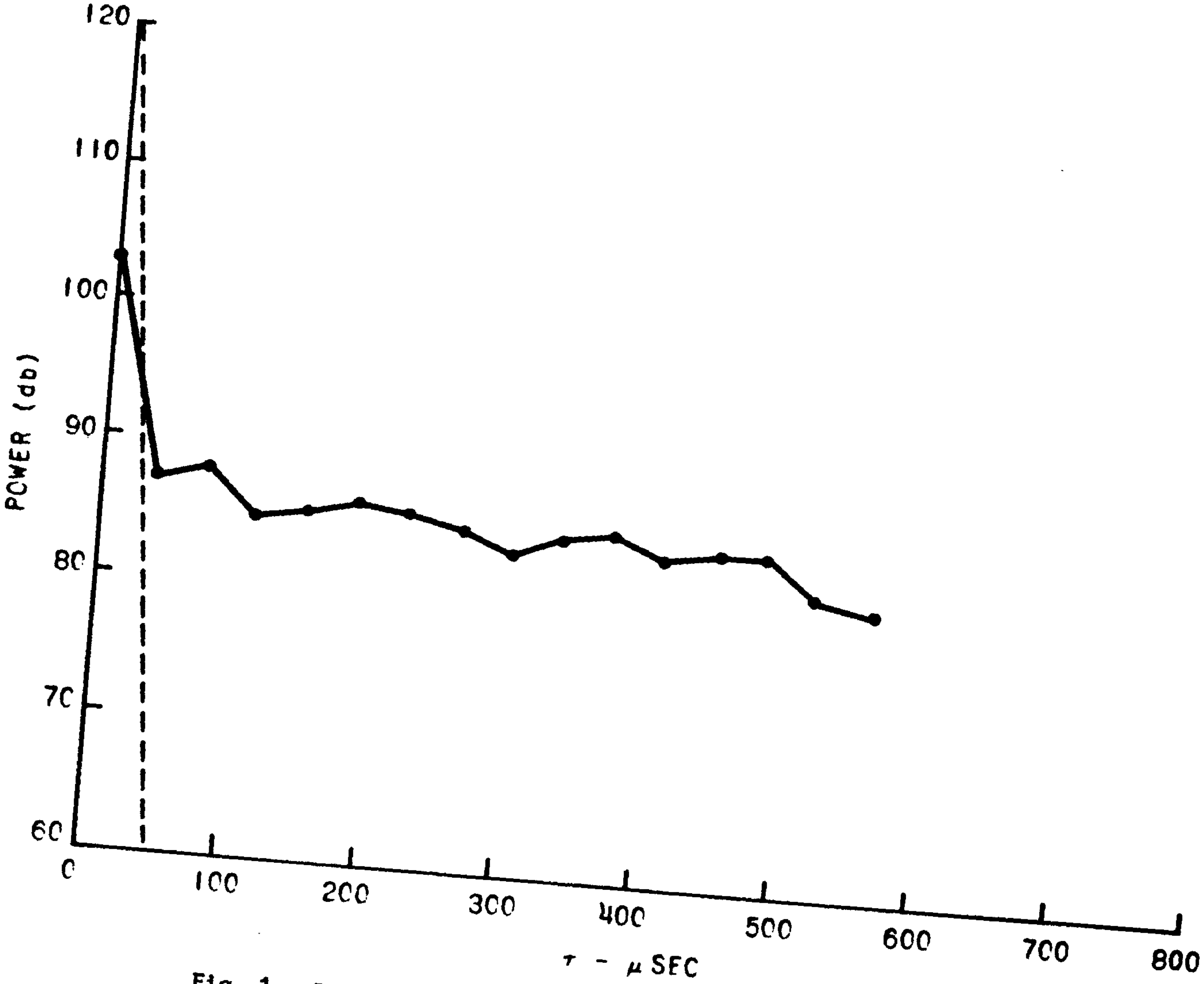

Fig. 1. Reflected power as a function of delay. The dotted line gives the power computed from equation 12.

DISTRIBUTION

	COPIES
Office of the Assistant Secretary of Defense (Research and Engineering) ATTN: Technical Library Room 3E1065, The Pentagon Washington 25, D. C.	1
Commanding General U. S. Army Electronics Command ATTN: AMSEL-AD Fort Monmouth, New Jersey	3
Chief of Research and Development Department of the Army Washington 25, D. C.	2
Chief, United States Army Security Agency ATTN: ACofS, G4 (Technical Library) Arlington Hall Station Arlington 12, Virginia	1
Commanding Officer U. S. Army Electronics Research & Development Activity ATTN: Technical Library Fort Huachuca, Arizona	1
Commanding Officer U. S. Army Electronics Research & Development Activity ATTN: SELWS-AJ White Sands, New Mexico	1
Commanding Officer U. S. Army Electronics Research Unit P. O. Box 205 Mountain View, California	1
Commanding Officer U. S. Army Electronics Materiel Support Agency ATTN: SELMS-ADJ Fort Monmouth, New Jersey	1
Headquarters, United States Air Force ATTN: AFCIN Washington 25, D. C.	2
Rome Air Development Center ATTN: RAALD Griffiss Air Force Base, New York	1

DISTRIBUTION

	COPIES
Ground Electronics Engineering Installation Agency ATTN: ROZMEL Griffiss Air Force Base, New York	1
Aeronautical Systems Division ATTN: ASAPRL Wright-Patterson Air Force Base, Ohio	1
U. S. Air Force Security Service ATTN: ESD San Antonio, Texas	1
Strategic Air Command ATTN: DOCE Offutt Air Force Base Nebraska	1
Air Proving Ground Center ATTN: PGAPI Eglin Air Force Base, Florida	1
Air Force Cambridge Research Laboratories ATTN: CRXL-R Laurence G. Hanscom Field Bedford, Massachusetts	2
AFSC Scientific/Technical Liaison Office U. S. Naval Air Development Center Johnsville, Pa.	1
Chief of Naval Research ATTN: Code 427 Department of the Navy Washington 25, D. C.	1
Bureau of Ships Technical Library ATTN: Code 312 Main Navy Building, Room 1528 Washington 25, D. C.	1
Chief, Bureau of Ships ATTN: Code 454 Department of the Navy Washington 25, D. C.	1
Hq, Electronic Systems Division ATTN: ESAT Laurence G. Hanscom Field Bedford, Massachusetts	2

DISTRIBUTION

	COPIES
Chief, Bureau of Ships ATTN: Code 686B Department of the Navy Washington 25, D. C.	1
Director U. S. Naval Research Laboratory ATTN: Code 2027 Washington 25, D. C.	1
Commanding Officer & Director U. S. Navy Electronics Laboratory ATTN: Library San Diego 52, California	1
Commander U. S. Naval Ordnance Laboratory White Oak Silver Spring 19, Maryland	1
Commanding Officer U. S. Army Engineer Research & Development Laboratories ATTN: Technical Documents Center Fort Belvoir, Virginia	1
Commanding Officer U. S. Army Chemical Warfare Laboratories ATTN: Technical Library, Building 330 Army Chemical Center, Maryland	1
Commander Armed Services Technical Information Agency ATTN: TISIA Arlington Hall Station Arlington 12, Virginia	20
USAELRDL Liaison Officer U. S. Army Tank-Automotive Center Detroit Arsenal Center Line, Michigan	1
Commanding Officer Harry Diamond Laboratories ATTN: Library, Building 92, Room 211 Washington 25, D. C.	1
USAELRDL Liaison Officer Naval Research Laboratory ATTN: Code 1071 Washington 25, D. C.	1

DISTRIBUTION

	COPIES
USAELRDL Liaison Officer Massachusetts Institute of Technology Building 26, Room 131 77 Massachusetts Avenue Cambridge 39, Massachusetts	1
USAELRDL Liaison Office Aeronautical Systems Division ATTN: ASDL-9 Wright-Patterson Air Force Base Ohio	1
U. S. Army Research Liaison Office Lincoln Laboratory P. O. Box 73 Lexington, Massachusetts	1
USAELRDL Liaison Officer Rome Air Development Center ATTN: RAOL Griffiss Air Force Base New York	1
Chief Scientist U. S. Army Electronics Command ATTN: AMSEL-SC Fort Monmouth, N. J.	1
USAEMSA Liaison Engineer USASCAJ A.P.O. 343 San Francisco, California	1
Technical Dir., SELRA/CS, Hq, USAELRDL	1
USAELRDA-White Sands Liaison Office, SELRA/LNW, USAELRDL	1
Corps of Engineers Liaison Office, SELRA/LNE, USAELRDL	1
Marine Corps Liaison Office, SELRA/LNR, USAELRDL	1
U. S. Army Combat Developments Command Liaison Office, SELRA/LNF USAELRDL	2
Commanding Officer, U. S. Army Security Agency Processing Center Fort Monmouth, N. J.	1
Chief, Technical Information Division, Hq, USAELRDL	6
USAELRDL Technical Documents Center, Hexagon	1

DISTRIBUTION

	COPIES
Dr. A. W. Straiton Electrical Engineering Research Laboratory University of Texas Austin 12, Texas	1
Dr. Homer E. Newell Office of Space Science NASA Headquarters Washington 25, D. C.	1
Professor William Gordon School of Electrical Engineering Cornell University Ithaca, New York	1
Dr. E. C. Jordan Dept. of Electrical Engineering University of Illinois Urbana, Illinois	1
Dr. Jules Aarons Propagation Laboratory Cambridge Research Center Hanscom Field Bedford, Massachusetts	1
Dr. V. R. Eshlemann Electronics Research Laboratory Stanford University Stanford, California	1
Dr. W. S. Ament Electromagnetic Research Corporation 5001 College Avenue College Park, Maryland	1
Dr. D. O. Muhleman Jet Propulsion Laboratory California Institute of Technology Pasadena, California	1
Dr. J. V. Evans Lincoln Laboratory Mass. Institute of Technology P. O. Box 73 Lexington 73, Massachusetts	1
Professor S. A. Bowhill University of Illinois Urbana, Illinois	1

DISTRIBUTION

	COPIES
Mr. Thos. Jos. Keary, U. S. Navy Electronics Laboratory San Diego 52, California	1
Professor H. D. Webb, Dept of Electrical Engineering University of Illinois Urbana, Illinois	1
Dr. Gordon H. Pettengill Lincoln Laboratory P. O. Box 73 Lexington, Massachusetts	1
Mr. Arthur B. Crawford Bell Telephone Laboratories, Inc. P. O. Box 107 Red Bank, New Jersey	1
U. S. Army Satellite Communications Agency Fort Monmouth, N. J. ATTN: Mrs. E. Rogers, Tech. Document Center	2
Professor S. Silver University of California Berkeley 4, California	1
Library, Boulder Laboratories National Bureau of Standards Boulder, Colorado	2
Collins Radio Company 855-35th Street, N. E. Cedar Rapids, Iowa ATTN: Irvin H. Gerks	1
Dr. John F. Clark Office of Space Science NASA Headquarters Washington 25, D. C.	1
Dr. R. Jastrow NASA Institute of Space Studies 475 Riverside Drive, New York, N. Y.	1
Dr. Donald F. Winter Applied Research Laboratory Sylvania Electric Products, Inc. 40 Sylvan Road Waltham 54, Massachusetts	1

DISTRIBUTION

	COPIES
Commanding General U. S. Army Materiel Command ATTN: R&D Directorate Washington 25, D. C.	2
Director, Institute for Exploratory Research, USAELRDL	1
File Unit (XS) Evans Area	1
Technical Staff, IER	50
Commanding General, U. S. Army Satellite Communications Agency ATTN: Technical Documents Center, Fort Monmouth, N. J.	1
Air Force Systems Command Scientific/Technical Liaison Office SELRA/LNA, USAELRDL	1
Hq, Research and Technology Division ATTN: RTH Bolling AF Base Washington 25, D. C.	1
USAELRDL Liaison Office USA Combat Developments Command ATTN: CDCLN-EL Fort Belvoir, Virginia	1
Mr. Robert J. Hackman United States Geological Survey Department of the Interior Washington 25, D. C.	1
Dr. W. H. Peake Ohio State University Antenna Laboratory Columbus, Ohio	1
Dr. Philip H. Abelson Geophysical Laboratory 2801 Upton Street, N. W. Washington 8, D. C.	1
Dr. Gerard P. Kuiper Lunar and Planetary Laboratories University of Arizona Tucson, Arizona	1
Jet Propulsion Laboratory California Institute of Technology Pasadena, California ATTN: G. S. Levy	1

DISTRIBUTION

	COPIES
The Rand Corporation 1700 Main Street Santa Monica, California ATTN: W. G. McMillan	1
University of California Observatory Space Sciences Laboratory Berkeley 4, California ATTN: A. Palm	1
University of Arizona Lunar and Planetary Laboratory Tucson, Arizona ATTN: D. P. Cruikshank	1
Boulder Laboratories National Bureau of Standards Boulder, Colorado ATTN: J. K. Hargreaves	1
Lincoln Laboratory Massachusetts Institute of Technology P. O. Box 73 Lexington 73, Massachusetts ATTN: Paul Green, Jr.	1

Army-Ft Monmouth,NJ-MON 1869-63

AD ______________ Div. ______________

Army Electronics Research and Development Laboratory, Fort Monmouth, N. J.
RADAR REFLECTION FROM A PLANETARY SURFACE DESCRIBED BY A COMPOSITE CORRELATION FUNCTION,
by Fred B. Daniels, May 1963, 13p. incl. illus. 20 refs. (USAELRDL Technical Report 2314)
(DA Task 3A99-25-003-04) Unclassified Report

An earlier theoretical study of radar reflection from a rough planetary surface is extended to include the case where the surface correlation function consists of two or more components. When both large- and small-scale structures are simultaneously present, it is found that the latter may completely dominate the autocorrelation function of the echo and thus render the former undetectable by c-w methods. An additional finding is that the large-scale structure may be detectable in the angular power spectrum obtained from very short pulses as a separate "pip" at the
(over)

UNCLASSIFIED

1. Planetary surface-composite correlation function
2. Moon-surface structure
3. Moon-dielectric constant
I. Daniels, Fred B.
II. Army Electronics Research and Development Laboratory
III. DA Task 3A99-25-003-04

UNCLASSIFIED

AD ______________ Div. ______________

Army Electronics Research and Development Laboratory, Fort Monmouth, N. J.
RADAR REFLECTION FROM A PLANETARY SURFACE DESCRIBED BY A COMPOSITE CORRELATION FUNCTION,
by Fred B. Daniels, May 1963, 13p. incl. illus. 20 refs. (USAELRDL Technical Report 2314)
(DA Task 3A99-25-003-04) Unclassified Report

An earlier theoretical study of radar reflection from a rough planetary surface is extended to include the case where the surface correlation function consists of two or more components. When both large- and small-scale structures are simultaneously present, it is found that the latter may completely dominate the autocorrelation function of the echo and thus render the former undetectable by c-w methods. An additional finding is that the large-scale structure may be detectable in the angular power spectrum obtained from very short pulses as a separate "pip" at the
(over)

UNCLASSIFIED

1. Planetary surface-composite correlation function
2. Moon-surface structure
3. Moon-dielectric constant
I. Daniels, Fred B.
II. Army Electronics Research and Development Laboratory
III. DA Task 3A99-25-003-04

UNCLASSIFIED

AD ______________ Div. ______________

Army Electronics Research and Development Laboratory, Fort Monmouth, N. J.
RADAR REFLECTION FROM A PLANETARY SURFACE DESCRIBED BY A COMPOSITE CORRELATION FUNCTION,
by Fred B. Daniels, May 1963, 13p. incl. illus. 20 refs. (USAELRDL Technical Report 2314)
(DA Task 3A99-25-003-04) Unclassified Report

An earlier theoretical study of radar reflection from a rough planetary surface is extended to include the case where the surface correlation function consists of two or more components. When both large- and small-scale structures are simultaneously present, it is found that the latter may completely dominate the autocorrelation function of the echo and thus render the former undetectable by c-w methods. An additional finding is that the large-scale structure may be detectable in the angular power spectrum obtained from very short pulses as a separate "pip" at the
(over)

UNCLASSIFIED

1. Planetary surface-composite correlation function
2. Moon-surface structure
3. Moon-dielectric constant
I. Daniels, Fred B.
II. Army Electronics Research and Development Laboratory
III. DA Task 3A99-25-003-04

UNCLASSIFIED

AD ______________ Div. ______________

Army Electronics Research and Development Laboratory, Fort Monmouth, N. J.
RADAR REFLECTION FROM A PLANETARY SURFACE DESCRIBED BY A COMPOSITE CORRELATION FUNCTION,
by Fred B. Daniels, May 1963, 13p. incl. illus. 20 refs. (USAELRDL Technical Report 2314)
(DA Task 3A99-25-003-04) Unclassified Report

An earlier theoretical study of radar reflection from a rough planetary surface is extended to include the case where the surface correlation function consists of two or more components. When both large- and small-scale structures are simultaneously present, it is found that the latter may completely dominate the autocorrelation function of the echo and thus render the former undetectable by c-w methods. An additional finding is that the large-scale structure may be detectable in the angular power spectrum obtained from very short pulses as a separate "pip" at the
(over)

UNCLASSIFIED

1. Planetary surface-composite correlation function
2. Moon-surface structure
3. Moon-dielectric constant
I. Daniels, Fred B.
II. Army Electronics Research and Development Laboratory
III. DA Task 3A99-25-003-04

UNCLASSIFIED